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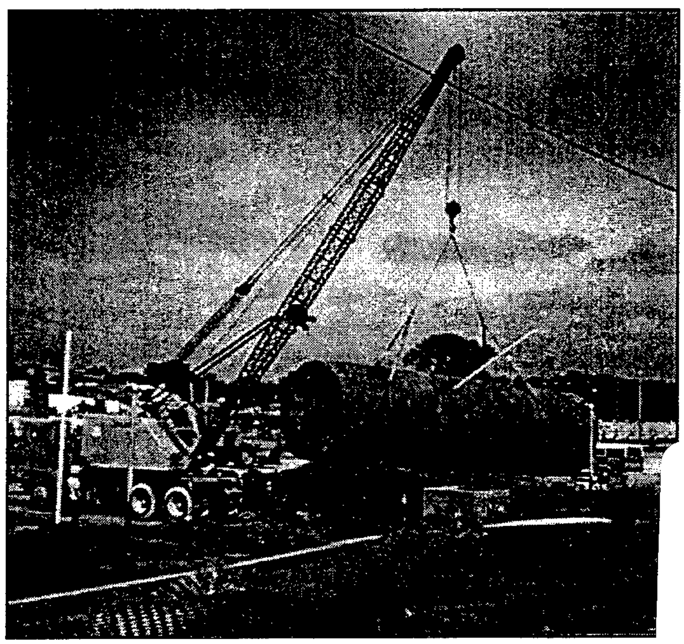
# Leak Potential Index Model for Use in Priority Ranking of Underground Storage Tanks at Formerly Used Defense Sites

by L.D. Stephenson

Abandoned underground storage tanks (UST) that have not been properly closed at formerly used defense sites may present potential leaking problems, spilling their hazardous contents into nearby soils, groundwater, and well water. The risk to the environment or population associated with the leaking USTs depends not only on the source, but on the migration pathway factor (i.e., the ability of the medium of transport—such as soil or water—to effectively transport the contaminants to the "receptor") and finally on the relative vulnerability of the potential receptor. Thus, the assessment of the relative risk begins with the calculation of the potential of the UST to leak. The Warren Rogers leak prediction model was developed circa 1981, and has been used for USTs and incorporated into leak prediction models for other types of underground steel structures.



The U.S. Army Construction Engineering Research Laboratories (USACERL) has recently modified the Rogers Leak Potential Index (LPI) Model for steel USTs by incorporating a wall thickness term. The resulting revised models express the age-at-leak as a function of surrounding soil parameters and tank geometric parameters. These new models were partially validated by comparing their predictions with observations from the TANKMAN database.

The leak prediction and probability models will be part of a triage program to prioritize the order of tank removal. The modified LPI (MLPI) provides useful LPI information if only minimal tank location and tank geometric data are available. Specifically, the MLPI requires only the knowledge of the UST's current age, its wall thickness (or capacity), and its geographic location within the United States.

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Abandoned underground storage tanks (USTs) that have not been properly closed at formerly used defense sites may present potential leaking problems, spilling their hazardous contents into nearby soils, groundwater, and well water. The risk to the environment or population depends not only on the source, but on the ability of the medium of transport—such as soil or water—to effectively transport the contaminants to the "receptor" and finally on the relative vulnerability of the potential receptor. Thus, the assessment of the relative risk begins with the calculation of the potential of the UST to leak.

The Warren Rogers Leak Potential Index (LPI) model was developed circa 1981 and has been used for USTs and incorporated into leak prediction models for other types of underground steel structures. USACERL modified the Rogers model for steel USTs by incorporating a wall thickness term. The resulting revised models express the age-at-leak as a function of surrounding soil parameters and tank geometric parameters. These models will be part of a triage program to prioritize the order of tank removal. The modified LPI (MLPI) provides useful LPI information knowing only the UST's current age, its wall thickness (or capacity), and its geographic location.

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# Foreword

This study was conducted for the Directorate of Military Programs Environmental Restoration Division for Formerly Used Defense Sites (FUDS) Branch, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Work Authorization Directive (WAD) F-97-97, Appropriation 2172020, "Leak Potential Index Model"; Work Unit B07, "Modify Existing Leak Potential Index (LPI) Model." The technical monitor was James Huang, CEMP-RF.

The work was performed by the Materials Science and Technology Division (FL-M) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Larry D. Stephenson. The author acknowledges the contributions of Dr. Charles Marsh, Vince Hock, and Vicki Van Blaricum of FL-M, James Wilcoski of the USACERL Facilities Engineering Division, and Prof. J. Carnahan of the General Engineering Dept. and Amer Siddique of the Nuclear Engineering Dept. at the University of Illinois, Urbana-Champaign. Dr. Ilker Adiguzel is Chief, CECER-FL-M; L. Michael Golish is Acting Operations Chief, CECER-FL. The USACERL technical editor was Linda L. Wheatley, Technical Information Team.

COL James A. Walter is Commander of USACERL, and Dr. Michael J. O'Connor is Director.

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# 1 Introduction

## Background

Abandoned underground storage tanks (USTs) that have not been properly closed at formerly used defense sites (FUDS) may present potential leaking problems, spilling their hazardous contents into nearby soils, groundwater, and well water. The leaking USTs are potential sources of contaminants generally classified as containerized hazardous, toxic, and radioactive waste (CON/HTRW). CON/HTRW includes petroleum, oil, and lubricants (POL), benzene, toluene, ethylbenzene, xylene (BTEX), and radioactive waste products. The risk to the environment and population associated with the leaking USTs depends not only on the source, but on the migration pathway factor (MPF) (i.e., the ability of the medium of transport—such as soil or water—to effectively transport the contaminants to the "receptor") and finally on the relative vulnerability of the potential receptor. Thus, the assessment of the relative risk begins with the calculation of the potential of the UST to leak. A method of predicting the risk of leakage of these USTs is therefore desirable. Presently, however, leak prediction index (LPI) models (which are used to predict the age at which a UST will leak or the probability of a UST leak at any given age) require soil data that are not readily available, or not easily and economically obtained by LPI-model users. The Warren Rogers leak prediction model was developed circa 1981, and has been used for USTs and incorporated into leak prediction models for other types of underground steel structures.

## Objective

The objectives of this research were to evaluate and demonstrate the applicability of modified LPI models as a protocol for ranking USTs at FUDS in terms of high, medium, or low probability of leaking with minimal input data (e.g., UST age, UST geometric parameters, and tank location).

## Approach

The current LPI was modified to provide a ranking index of "high" "medium" or "low" leak potential as a function of only UST age, UST geometric parameters, and tank location for steel USTs. This modification was based on information available to USACERL as in-house data, including data on leaking and non-leaking tanks in the TANKMAN database. Leak age prediction and probability as calculated by the modified LPIs will be compared with existing tank status. Performance of the candidate modified LPIs regarding their ability to predict UST leak status was correlated with the known UST status.

## Scope

This report describes the results of a research program to develop an LPI protocol for the prioritization of abandoned UST removal at FUDS. The results are based on application of the principles of mathematical modeling, soil science, and corrosion science to the analysis of available UST geographic location information, and the three major parameters of UST age, geometry, and leak data. The product of this research is a user-friendly leak prediction/probability model that provides a ranking index of "high," "medium," or "low" leak potential. A method of assessing the leak risk of concrete USTs is also presented in this report.

## Mode of Technology Transfer

It is suggested that the LPI model and protocol be incorporated into U.S. Army Corps of Engineers' standing procedures for selection and prioritization of UST removals at FUDS.

# 2 Database, Early Work, and Modification

## Rogers Leak Age Prediction Model

A report from Warren Rogers (circa 1980), *Report on the Statistical Analysis of Corrosion Failures [on] Unprotected Underground Steel Tanks*, provided a starting point for the work reported here. It provides (1) a set of detailed UST geometry and surrounding soil data with UST leak age information, and (2) a widely recognized semi-empirical leak prediction model rooted in well-established corrosion chemistry principles and basic corrosion rate formulae (Fontana 1986). However, the Rogers Canadian Tank Study does not include the effects of "tank wall thickness." This parameter is relevant because, given that all other things are equal, it is expected that tanks with a higher wall thickness will develop leaks at a later age.

The relevant parameters in the Rogers leak age prediction equation (WR) are the "response" variable *age*, or "predicted leak age" (PLA), as a function of the "predictor" variables: tank capacity (S), the tank's original wall thickness (T), soil resistivity (R), and soil chemistry (e.g., pH), relative moisture content (M), and relative sulfide content (Su). (Note that S is measured in gallons, T is measured in inches, R is measured in ohm-cm, and pH, M, and Su are dimensionless. Rogers established that M = 1 if the soil is saturated; otherwise, M = 0. Su = 1 if sulfides are present; otherwise, Su = 0.) A complete list of these and other abbreviations and acronyms appearing in this report is also provided in Appendix A. To incorporate the effects of a tank's original wall thickness, it is first necessary to correlate "size" (or "capacity") data with typical wall thickness measurements. It is also necessary to make the assumption that the tank capacities referenced in the WR data can be correlated with tank wall thicknesses in accordance with Table 1. For each model considered, the residual standard deviations are used as a means of comparing the equations. (Residual is defined as the difference between the actual age given in the data set and the leak age predicted by the model under consideration.) Furthermore, each equation is scrutinized for its ability to adequately predict "reasonable and believable" PLA values when extrapolated to the most corrosive and least corrosive conditions, as will be explained in Chapter 4, p 18. These leak prediction models are based on the generally accepted corrosion engineering hypothesis

Table 1. UST shell thickness as a function of tank capacity.

| Tank Capacity (gal)[a] | Shell Thickness (in.)[b] |
|---|---|
| ≤285 | 0.078 |
| 286 to 550 | 0.109 |
| 551 to 1,500 | 0.141 |
| 1,501 to 4,000 | 0.188 |
| 4,001 to 11,600 | 0.250 |
| 11,601 to 20,000 | 0.313 |
| 20,001 to 30,000 | 0.375 |
| 30,001 to 100,000 | 0.500 |
| ≥ 100,000 | 0.625 |

(Source: Underwriter's Laboratories Standards UL58/UL746.)
[a] 1 gal = 3.785 liters
[b] 1 in. = 25.4 mm

that localized anodes are necessary for the development of corrosion leading to perforation (Rogers, circa 1980).

Soil parameters are especially relevant for USTs that are improperly installed (e.g., when the tank is buried in direct contact with the soil). Indeed, field experience indicated that the part of the tank most likely to develop leaks is the bottom third (USACERL, November 1995). This information is consistent with observations that, in the past, many tanks were buried with no backfill on the bottom, but with backfill added on the tops and sides (Hock 1995). Also, the bottom third of the UST is more likely to suffer exposure to the water table, which is conducive to corrosion (Berg, January 1996).

## Modification of the Rogers Model

USACERL undertook the development of a localized corrosion leak prediction/probability model for steel USTs as a function of soil parameters and tank geometric factors to be used in conjunction with the U.S. Environmental Protection Agency's (EPA's) 1995 EPA study (as dictated by ASTM* ES 40-94). As part of this study, pit depths (resulting from localized corrosion) in the walls of USTs will be determined using a robotically operated *in situ* ultrasonic thickness measurement device. Knowledge of the maximum pit depth at a given age could then be extrapolated to predict the age at which perforation will occur. A leak prediction/probability model could also be used as part of a triage program to determine the order in which tanks should be examined.

The leak prediction model is to be expressed as a function of tank age (i.e., its time of exposure to the corrosive environment) in addition to the tank's

* ASTM = American Society for Testing and Materials.

dimensions and the surrounding soil parameters. First, a tank wall thickness term will be incorporated into the existing leak prediction model given by Rogers (circa 1980), in order to produce a revised model that expresses the time-to-leak as a function of soil parameters and all relevant tank geometric parameters (including original wall thickness). The resulting equation can then be re-arranged to predict the maximum pit depth as a function of the tank's age (i.e., the time of exposure to the corrosive conditions), and the applicable tank geometry and soil parameters.

The original Rogers Leak Prediction Model expressed the time-to-leak as a function of tank capacity (size), and soil resistivity, pH, moisture, and sulfide content. The modified Rogers Model (thickness term included) will state that:

$$PLA = f(R, S, T, pH, M, Su) \qquad \text{[Eq 1]}$$

This equation can be rearranged to:

$$T = g(PLA, R, S, pH, M, Su) \qquad \text{[Eq 2]}$$

where "f" and "g" represent mathematical functions.

For a leaking tank, the maximum pit depth ($p_{max}$), equals T, when the time of exposure to the corrosive environment, or PLA equals the tank's age at a given point in time (or "age at the time of inspection"). That is,

$$T = p_{max} \ @ \ PLA = Age$$

Therefore, for that same tank under the same set of conditions at *any* age, the maximum pit depth can be determined by:

$$p_{max} = g(Age, R, S, pH, M, Su) \qquad \text{[Eq 3]}$$

The WR Canadian data set used in this study included data from 60 leaking tanks and 127 nonleaking tanks. The sample observed mean ages and standard deviation for the sample of leaking tanks were 18.22 years and 5.21 years, respectively. The sample mean ages and standard deviation for the nonleaking tanks were 14.69 years and 7.03 years, respectively.

The leak prediction model derived by Rogers can be stated as:

$$PLA = [(5.57R^{0.05}S^{-0.018})] \, [\exp(0.13pH - 0.41M - 0.26Su)] \qquad \text{[Eq 4]}$$

where PLA = age (in years) to first leak. Only data for the leaking tanks were used in the regressions. The nonleaking tank data were then used to validate the revised model, since the model should predict future leaks for nonleaking tanks.

In 1992, Guglomo et al. described the MicroGPIPER (MGP) model, which was developed for underground steel pipes by modifying the original WR Model to include the effects of wall thickness. In that report, pipe data were statistically fitted to produce the MGP Model, which is stated as:

$$PLA = 23.5 + \{[45.9R^{0.05}S^{-0.018}T^{2.7}]\,[\exp(0.13pH - 0.41M - 0.26Su)]\} \qquad \text{[Eq 5]}$$

The MGP Equation incorporates the effects of wall thickness for USTs (Equation 3), based on a Romanoff maximum pit depth equation of the form:

$$p_{max} = kt^{n} \qquad \text{[Eq 6]}$$

where $p_{max}$ = maximum pit depth, t = time exposure to corrosive environment, and k = a calibration constant (Romanoff 1957). According to Rossum (1969), "n" should range from 1/6 to 2/3, depending on the level of soil aeration.

# 3 Description of New Models

## New Models

The form chosen for the revised candidate leak prediction models is given as follows:

$$PLA= AR^{B}S^{C}E^{D}T^{F} \quad \text{[Eq 7a]}$$

where:

$$E\equiv\exp[(\alpha pH)+(\beta M)+(\gamma Su)]. \quad \text{[Eq 7b]}$$

This product form is appealing because it yields reasonable PLA values when extrapolated to lower boundary conditions (i.e., PLA $\rightarrow$ 0 as T$\rightarrow$0, R$\rightarrow$0, S$\rightarrow$0), which is also true for the original Rogers model). The theoretical framework for this multiplicative model was established by Rossum (1969) and either appropriated or independently derived by subsequent investigators. Rogers used a different form for the "pH" term, and introduced the "moisture" and "sulphide" terms.

The resulting models were not regarded as valid *if* they did not seem to have coefficients and exponents of the right sign. For example:

1. PLA should increase as R or T increases; therefore, the exponents of these parameters must be positive.

2. PLA should increase as pH increases; therefore, the coefficient in the argument of the exponent must be positive.

3. PLA should decrease as M or Su increases; therefore, the coefficients of M and Su in the argument of the exponent must be negative.

4. The models should give reasonable and believable values based on field data and experience, especially when extrapolated to boundary limits.

Note that these criteria are all based on application of well-established physical principles of corrosion science and empirical rules of the corrosion process (Fontana 1986).

For the parameter S, the sign of the exponent is not as obvious, and good arguments exist for it to be either negative or positive. One might expect PLA to decrease as S increases, as a result of increased chances that corrosion will occur over a larger surface area exposed to the corrosive environment. This expectation would indicate a negative exponent for S. However, the exponent of S could be positive since (as indicated in Table 1) as S increases, T also increases. The increase in T, however, is not a continuous function of S, but occurs in steps (i.e., a constant value of T exists over a specific size interval, and once the size interval threshold is exceeded, the T values increase to the next level, as in Table 1). Also, for the range of sizes in the WR data only four thickness values apply.

Actually, the more useful predictive parameter may be "surface area"; a larger surface area would result in a greater chance of corrosion. Also, a tank with a larger surface area will more likely corrode due to a higher ratio of cathode area to anode area, with the earliest pit acting as the anode, and the uncorroded portion of the tank wall acting as the cathode. In that case, it is suggested that future models use "surface area" as a predictor, rather than capacity. (Unfortunately, the surface area information is not always available, but because USTs are typically constructed according to UL58, a correlation generally exists between capacity and area.) Indeed, other researchers indicate the importance of considering surface area as a relevant parameter. Some models actually include the surface area term in lieu of capacity (Rogers 1990).

Three variations on the exponential term of the leak prediction model were considered. The three models resulting from these regressions were generated by:

1. restricting the values of $\alpha,\beta,\gamma$ to those given by the Rogers Model.

2. multiplying each of the Rogers values of $\alpha,\beta,\gamma$ (sometimes called "chemistry parameters") by the same scaling factor, determined by the regression analysis. (Note that this is also equivalent to raising the "exp term" in the original Rogers equation to a power equal to the scaling factor.)

3. imposing no restrictions on the values of $\alpha,\beta,\gamma$.

## Results

The age at which a leak occurs (PLA) is assumed to be a normal random variable for which an expectation value can be predicted (to some degree) as a function of six explanatory variables (R, S, T, pH, M, and Su).

### *First Variation*

Starting with the product form of the revised model as cited earlier, and taking logarithms, a linear equation of the form results:

$$\ln(PLA)-\ln(E) = \ln(A) + B\ln(R) + C\ln(S) + F\ln(T) \qquad \text{[Eq 8]}$$

Note that, by placing "ln(E)" on the left side of the equation, it forms part of the "response" variable. The full response variable is now "ln(PLA)-ln(E)". In this case, the value of "E" is computed by using the values of $\alpha,\beta,\gamma$ as given in the Rogers Model. (Recall that $E \equiv \exp[(\alpha pH)+(\beta M)+(\gamma Su)]$). The predictor variables are "ln(R)," "ln(S)," "ln(T)." Now the least squares multiple linear regression is performed using Excel® and Statistica™, and the constants ln(A), B, C, and F are determined. Finally, the inverse transformation is performed, and the original form of the equation, given by 7a and 7b, is restored:

$$PLA= AR^{B}S^{C}E^{D}T^{F}$$

where: $A = 23.03$

$B = 0.03388$

$C = -0.1063$

$D = 1$

$F = -0.07220$

with a residual standard deviation of 5.58 years, and coefficient of determination, $r = 0.1788$. It is obvious that this model is not valid, because the exponent of T is negative, and this clearly violates physical principals. Furthermore, the coefficient of determination is very low.

### *Second Variation (Scaled Model)*

The logarithmic transformation can be rewritten so that "ln(PLA)" is the response variable and "ln(E)" forms one of the predictor variables along with "ln(R)," "ln(S)," and "ln(T)" in the form of:

$$\ln(PLA) = \ln(A) + B\ln(R) + C\ln(S) + D\ln(E) + F\ln(T) \qquad \text{[Eq 9]}$$

In this case, the coefficient D acts as a scaling factor, which in effect, multiplies the original Rogers values of $\alpha,\beta,\gamma$ by "D" (i.e., this version of the model allows variations in the chemistry parameters appearing in the argument of exp). The best-fitting logarithmic transformation model of this type is:

A = 12.0395

B = 0.100954

C = -0.052313

D = 1

F = 0.115821

$\alpha = 0.048945$

$\beta = 0.154364$

$\gamma = -0.097889$

This log-transformed multiple regression model yields a residual standard deviation of 4.99 years, and coefficient of determination, r = 0.3555.

The original product form of the model can also be restored with an inverse logarithmic transformation. Note that this model has $\alpha,\beta,\gamma$, which are equal to the original Rogers Model values scaled (multiplied) by 0.376498 (determined from regression analysis). The signs and magnitudes of the coefficients and the coefficient of determination all indicate that this model is physically valid.

### *Third Variation*

The final variation in the new leak prediction model was obtained by imposing no restrictions on the chemistry parameters, $\alpha,\beta,\gamma$. This model was derived by nonlinear regression using Statistica™. It results in slightly lower residuals and standard deviations (STDs) than the previous models, and the values of the coefficients are found to be:

$A = 32.777810$

$B = 0.085892$

$C = -0.153936$

$D = 1$

$F = 0.388414$

$\alpha = 0.082545$

$\beta = -0.004122$

$\gamma = -0.119086$

with a residual standard deviation of 4.81 years, and a multiple coefficient of determination, r = 0.3828. As in the first two variations, the original product form of the model can also be restored with an inverse logarithmic transformation.

As with the second variation model, the signs and magnitudes of the coefficients and the coefficient of determination all indicate that this model is physically valid.

# 4 Discussion and Applications

Figures 1 and 2 show the predicted leak age and the actual leak age plotted against the tank identity (WR Canadian USTs numbered 1 through 60) for the two valid models.

The mean leak ages and variances predicted by both new models are in relatively good agreement with the raw data (observations) from the WR Canadian data set, as would be expected from regression analysis. For each of the new models, Table 2 gives the predicted mean leak age of the sample and sample standard deviation for leaking tanks. Although data for only *leaking* tanks were used in generating these models, the validity of each model was tested by computing PLAs for the nonleaking tanks. In both models presented here, the *nonleaking* tank data predicted PLAs that are generally higher than their inspection ages (denoted as "observations" in Table 2), as should be expected (i.e., these new models typically predict *future* leaks for "nonleaking tank data"). For the nonleaking tanks, the predicted mean leak age of the WR Canadian sample and sample standard deviation are given in Table 2. Furthermore, both models gave reasonable and believable values when extrapolated to extreme conditions (i.e., those that are the most and least conducive to corrosion), as provided by archival data given in Table 3.

The relatively low coefficient of determination, "r" ranging from 0.3555 to 0.3828, indicates that other factors not considered in these equations are involved.

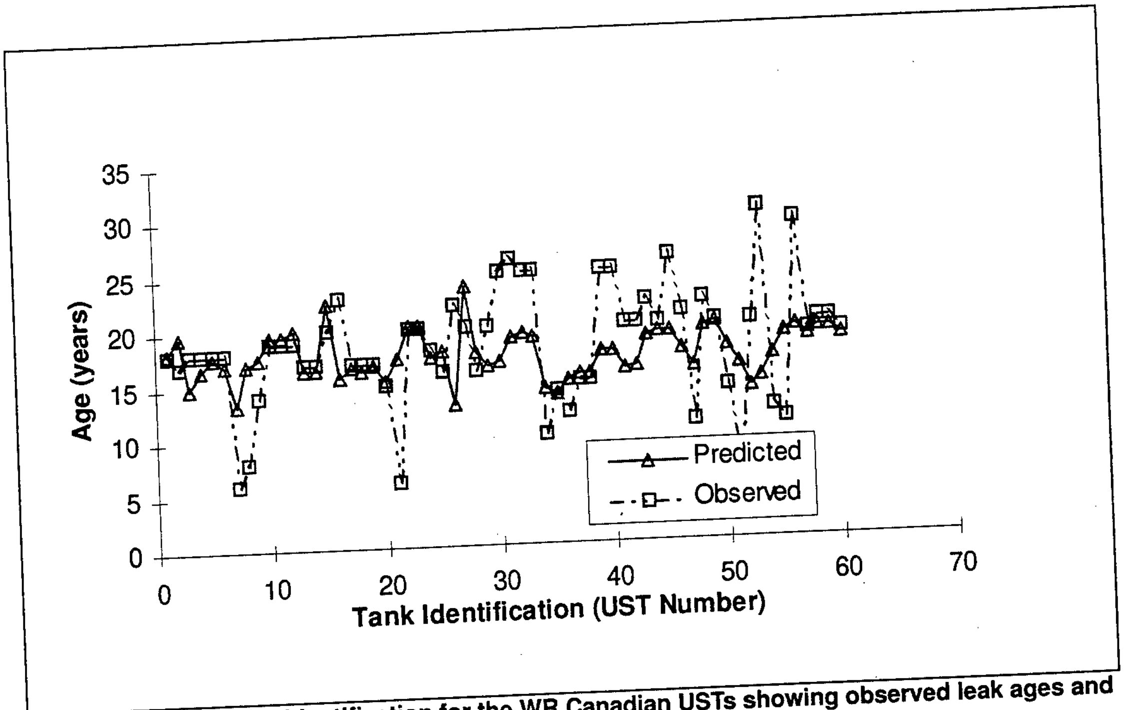


**Figure 1. Age vs. tank identification for the WR Canadian USTs showing observed leak ages and predicted leak ages using variation 2, the multiple regression (scaled) model.**

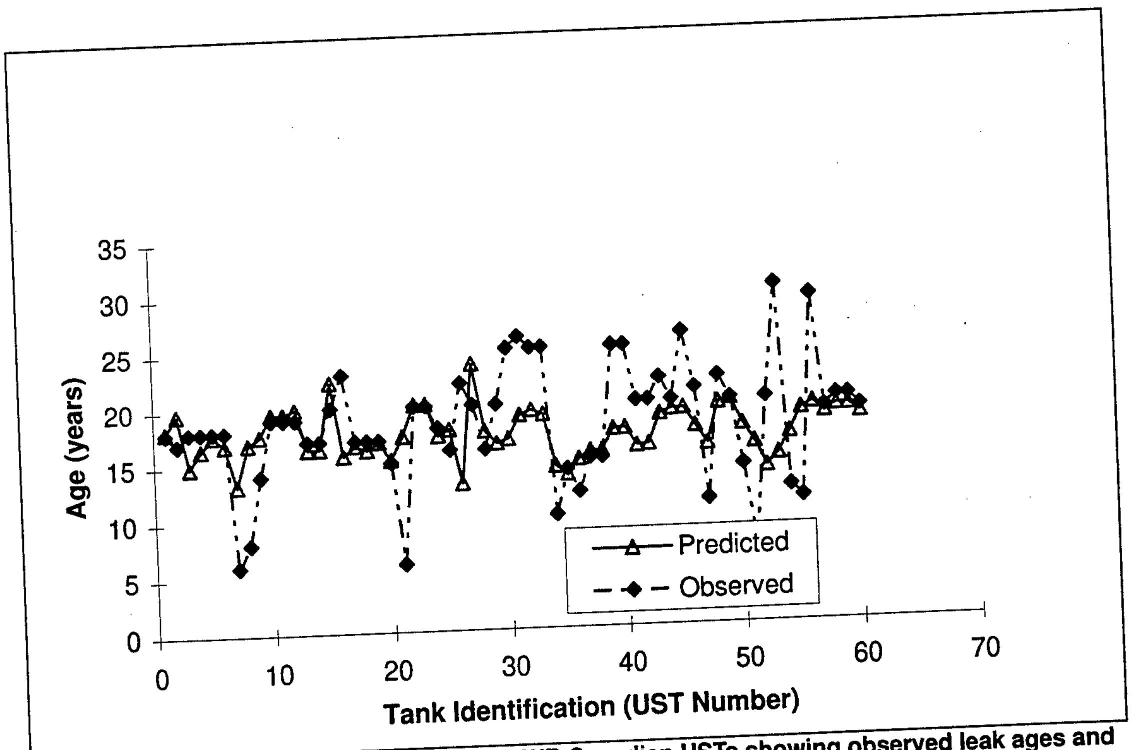


**Figure 2. Age vs. tank identification for the WR Canadian USTs showing observed leak ages and predicted leak ages using variation 3, the nonlinear model.**

Table 2. Mean and standard deviations for predicted leak ages and age at time of inspection for both leaking and nonleaking USTs and residual standard deviations for linear and nonlinear leak prediction models.

| UST Status; Raw Database(s) Used | Data Source (Observations or Predictive Model) | Mean (yr) | STD (yr) | Model Residual STD (yr) |
|---|---|---|---|---|
| 60 Leaking Canadian USTs | Observations (Age at Inspection) | 18.22 | 5.21 | N/A |
| 60 Leaking Canadian USTs | Predictive Model–Second Variation: Scaled (linear) Model | 17.45 | 2.13 | 5.16 |
| 60 Leaking Canadian USTs | Predictive Model–Third Variation: Nonlinear Model | 18.22 | 1.98 | 5.07 |
| 83 Leaking (60 Canadian and 23 TM* USTs) | Observations (Age at Inspection) | 20.00 | 9.34 | N/A |
| 83 Leaking (60 Canadian and 23 TM USTs) | Predictive Model– Second Variation: Scaled (Linear) Model | 18.57 | 2.80 | 9.10 |
| 83 Leaking (60 Canadian and 23 TM USTs) | Predictive Model–Third Variation: Nonlinear Model | 18.16 | 1.94 | 9.88 |
| Nonleaking 127 Canadian USTs | Observations (Age at Inspection) | 14.69 | 7.03 | N/A |
| Nonleaking 127 Canadian USTs | Predictive Model–Second Variation: Scaled (Linear) Model | 16.48 | 1.93 | N/A |
| Nonleaking 127 Canadian USTs | Predictive Model-Third Variation: Nonlinear Model | 18.72 | 2.48 | N/A |

*TM = TANKMAN.

Table 3. Archival data and predicted leak ages for the linear scaled model and the nonlinear model as a function of selected soil and geometric parameters.

| Case # | Resistivity (R) (ohm-cm) | Capacity (S) gal | (liters) | Thickness (T) In. | (mm) | pH | Saturation Index (M) | Sulphur Index (Su) | Predicted Leak Age (Scaled Model) (yr) | Predicted Leak Age (Nonlinear Model) (yr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 61 | 285 | (1,079) | 0.078 | (1.98) | 4.1 | 1 | 1 | 9.59 | 9.00 |
| 2 | 900 | 285 | (1,079) | 0.078 | (1.98) | 5.7 | 1 | 1 | 13.61 | 12.94 |
| 3 | 5,000 | 10,000 | (37,853) | 0.25 | (6.35) | 6 | 1 | 1 | 15.60 | 13.97 |
| 4 | 13,000 | 10,000 | (37,853) | 0.3 0 | (7.62) | 6.5 | 1 | 1 | 17.98 | 16.97 |
| 5 | 24,000 | 10,000 | (37,853) | 0.35 | (8.89) | 7 | 0 | 1 | 23.28 | 19.87 |
| 6 | 48,000 | 10,000 | (37,853) | 0.35 | (8.89) | 8 | 1 | 0 | 24.78 | 25.70 |
| 7 | 60,000 | 5,000 | (18,927) | 0.40 | (10.16) | 8.5 | 0 | 0 | 31.92 | 32.12 |
| 8 | 89,000 | 30,000 | (113,560) | 0.50 | (12.7) | 9 | 0 | 0 | 31.81 | 28.66 |
| 9 | 89,000 | 10,0000 | (378,533) | 0.625 | (15.9) | 9.7 | 0 | 0 | 31.71 | 27.51 |

For example, the observed leak age in the raw data indicates only that the tanks were leaking at the time of inspection; it does not indicate the age at which the tanks actually began to leak.

Table 4 shows the correlation matrix for this data set, and indicates that R, pH, and Su are the most significant regressors. Furthermore, the correlation matrix indicates the very strong correlation between T and S (a problem that was noted earlier), and an apparently coincidental correlation of sorts between Su and T. Because of the strong correlation between S and T, the regression equations may be ill-conditioned. Unfortunately, it appears that the operative corrosion mechanisms here require that both S and T be considered as independent predictor parameters; therefore, they were both treated accordingly in the regressions.

Rogers (1990) indicated that when his initial model was "revised to reflect the time lag from initial perforation to detection," the exponent of size (S) shifted to a positive number. According to Rogers, the time lag apparently compensates for the tendency of smaller UST leaks to be detected later than leaks in larger USTs. No further details on the "time lagged" revision are available at this time.

**Table 4. Correlation matrix for parameters in the Canadian set of 60 leaking USTs.**

| Variable | Resistivity (R) | pH | SAT | Su | Capacity (S) | Age | Thickness (T) |
|---|---|---|---|---|---|---|---|
| R | 1.00 | -0.05 | -0.11 | -0.12 | 0.05 | 0.17 | 0.12 |
| pH | -0.05 | 1.00 | -0.04 | 0.20 | 0.04 | 0.19 | 0.00 |
| SAT | -0.11 | -0.04 | 1.00 | 0.16 | -0.21 | -0.06 | -0.20 |
| Su | -0.12 | 0.20 | 0.16 | 1.00 | -0.29* | -0.20 | 10.37* |
| S | 0.05 | 0.04 | -0.21 | -0.29* | 1.00 | -0.08 | 0.94* |
| Age | 0.17 | 0.19 | -0.06 | -0.20 | -0.08 | 1.00 | 0.03 |
| T | 0.12 | 0.00 | -0.20 | -0.37* | 0.94* | 0.03 | 1.00 |

Note: Marked correlations (*) are significant at $p<0.05000$; N=60.

# 5 Validity of the New Models

The validity of the revised Rogers models was further tested against an independent set of data taken from the USACERL TANKMAN (TM) database. Unfortunately, the TM data contained no information on moisture content (M), or sulfide content (Su); however, for the 23 leaking tanks from the TM database, arbitrary assignments were made for the saturation and sulfide indices (e.g., M = 0 and Su = 0). These assignments may be justified because soils in the areas where 21 out of 23 of these tanks were located (e.g., Fort Bliss, Texas) are generally drier and more often devoid of sulfides than are the soils in which the WR tanks were located (USDA, November 1971). When the new predictive models (generated using the WR data for the 60 leaking tanks) were applied to the 23 TM leaking tanks, the average predicted leak age was about 7.5 to 8 years less than the average actual leak age. When these models are applied to the integrated set of 83 leaking USTs (i.e., 60 leaking Canadian USTs from the WR database and 23 leaking USTs from the TM database), they predicted mean leak ages about 1 to 2 years earlier than observed mean leak age for the integrated set (see Table 2). The correlation matrix for this integrated data set is shown in Table 5, and indicates that, again, size and thickness are highly correlated, and that pH, Su, and M are also somewhat correlated.

Next, the data for 23 leaking tanks from the TM database were combined with the Rogers data for 60 leaking Canadian tanks, and a new predictive equation was generated by regressing the leak age parameter on the independent variables resistivity (R), capacity (S), wall thickness (T), and pH.

The results of the nonlinear regression for the integrated set of data for the 83 leaking tanks indicated similar regressed values for the exponents for R and S, (based on the multiplicative model in Equation 7) but higher regressed exponents for T and pH. The nonlinear regression then yielded the following results:

$A = 256.6$

$B = 0.072624$

$C = -0.194713$

$D = 1$

$F = 0.862292$

$\alpha = 0.000392$

$\beta = -0.195012$

$\gamma = -0.067732$

with a coefficient of determination, r = 0.4554, and a residual standard deviation of 8.64 years.

This result indicates that wall thickness plays a much stronger role in these predictive equations when the TM data set is included, as was indicated by the correlation matrix in Table 5. It is clear that the exponent is significantly less than the lower limit of 1.5 predicted by the pipe models attributed to Rossum and Romanoff (see Equation 10). It is encouraging that the exponents of R and S did not vary significantly from the values obtained in the regression analysis for the non-linear (third variation) model. Indeed, the Table 5 correlation matrix indicates that R, pH, and Su are the more significant explanatory parameters.

Finally, it should be noted that Rossum indicates that the exponent of T may not be a constant, but may actually vary with soil type. This concept should be more thoroughly examined in future data analyses. For example, a leak prediction model could be investigated for which the exponent of T is a function of some of the soil parameters. Such an analysis would likely require an immense and detailed set of leaking tank data from many geographic regions throughout North America.

**Table 5. Correlation matrix for parameters in the Canadian set of 60 leaking USTs integrated with the 23 leaking tanks from the TANKMAN database.**

| Variable | Resistivity (R) | pH | SAT | Su | Capacity (S) | Age | Thickness (T) |
|---|---|---|---|---|---|---|---|
| R | 1.00 | -0.24* | -0.29* | -0.24* | 0.25* | 0.23* | 0.23* |
| pH | -0.24* | 1.00 | 0.62* | 0.53* | -0.30* | -0.23* | -0.19 |
| SAT | -0.29* | 0.62* | 1.00 | 0.54* | -0.37* | -0.34* | -0.28* |
| Su | -0.24* | 0.53* | 0.54* | 1.00 | -0.29* | -0.29* | -0.32* |
| S | 0.25* | -0.30* | -0.37* | -0.29* | 1.00 | 0.28* | 0.84* |
| Age | 0.23* | -0.23* | -0.34* | -0.29* | 0.28* | 1.00 | 0.28* |
| T | 0.23* | -0.19 | -0.28* | -0.32* | 0.84* | 0.28* | 1.00 |

Note: Marked correlations (*) are significant at p<0.05000; N=60.

# 6 Leak Probability Calculation

Using Equations 7a and 7b with coefficients and STD for the nonlinear (third variation) model, the probability of leak at any age, Pr(z), is equal to the area under the normal probability curve corresponding to z, where,

$$z = [\text{Age-PLA}]/\text{STD} \qquad [\text{Eq } 10]$$

where:

Age = Current age

PLA = Predicted age-at-leak (from Equation 7a, 7b)

STD = Standard deviation of predicted leak age

Pr (z) = Probability that leak has occurred at the age corresponding to z.

Values of areas under the normal curve can be found in tables provided in many statistical references (e.g., Guttman et al. 1971). For example, when "Age = PLA – STD," the statistic z = -1; therefore, the probability is 16 percent that the tank is leaking. At "Age = PLA + STD," the statistic z = +1; therefore, the probability is 84 percent that the tank is leaking. Using the above algorithm, the USTs are ranked according to a modified leak potential index (MLPI) numbers 1, 2, 3, corresponding to Low, Medium, or High potential for leaking.

Table 6 illustrates how the z value calculated in Equation 10 relates to the probability of leaking and the MLPI assigned to that leak probability range.

**Table 6. Modified Leak Potential Index (MLPI) ratings for USTs and corresponding leak probability and z statistic.**

| MLPI (verbal) | MLPI (numerical) | Leak Probability | z |
|---|---|---|---|
| Low | 1 | < 50% | <0 |
| Medium | 2 | 50% to 84% | 0 to 1 |
| High | 3 | > 84% | >1 |

A rudimentary version of the PLA prediction algorithm is based on the parameters of typical moderately corrosive soil wherein R = 5000 ohm-cm, pH = 6, M = 1, and Su = 0. The only required input parameters are UST age and capacity (or wall thickness). Confidence in the calculated MLPI can be improved if the soil parameters resistivity, pH, moisture, and sulfide content are known. These data are available by determining the soil series for the location at which the UST is installed using information from the U.S. Geological Survey (USDI 1970). The world-wide web (WWW) database known as Iowa State University's "statlab" can then be queried on the desired soil parameters of the soil series. This database can be accessed via the Internet address: "http://www.statlab. iastate.edu/soils." This information can be accessed also through the database maintained by the U.S. Department of Agriculture (USDA) National Resources Conversation Service (NRCS) via the internet address: "http://www.ncg.nrcs.usda.gov/muir. html." Furthermore, archival soil data gathered by the National Bureau of Standards (Appendix B) provides a useful list of soil types and their relevant parameters for selected locations throughout the United States (Romanoff 1957). If required soil information is not listed in Appendix B for the desired location, then the soil parameters for the nearest location will probably be useful. These options are summarized in flow chart format in Appendix C.

# 7 Summary for Steel and Concrete USTs

## Steel USTs

A revised variation of the Rogers Leak Prediction/Probability Model for steel USTs has been developed. In this work, a thickness term was incorporated into the localized corrosion leak prediction model initially developed by Rogers, which expressed age-at-leak as a function of soil parameters and tank capacity. The age at leak was assumed to be a normal random variable for which an expectation value can be predicted (to some degree) as a function of the soil and tank geometric parameters. The Canadian data set of 60 leaking tanks and 127 nonleaking tanks as provided by Rogers was analyzed by least squares multiple regression and nonlinear regression using Statistica and Excel®. For 60 leaking USTs for the Canadian data set, the resulting models expressed the age-at-leak as a function of the tank's original wall thickness and capacity, and the surrounding soil's resistivity, pH, moisture, and sulfide content, with the regression coefficient "r" ranging from 0.3555 to 0.3828 and residual standard deviations ranging from 5.07 to 5.16 years. Partial confirmation of the new models was provided by incorporating data for 23 leaking tanks from the USACERL TANKMAN database; however, the TM data indicated a considerably larger exponent for the thickness variable.

The mean and variance of the predicted leak ages for the sample of 60 leaking tanks are in accordance with the observations. Future leaks are predicted for the currently nonleaking tanks. The probability of a leak occurring at any given time can be determined by computing the area under the normal distribution curve, which then converts the probability into a model for ranking the potential of leaking at a given age. The ranking is given in the form of a modified leak potential (MLPI) number 1, 2, or 3, corresponding to low, medium, or high potential for leaking. The only required input parameters are UST age and capacity (or wall thickness). The confidence in the MLPI can be improved if the soil parameters resistivity, pH, moisture, and sulfide content are known. These data are obtained from the U.S. Geological Survey resource giving the location at which the UST is installed (USDI 1970), and the WWW statlab database maintained at Iowa State University, which provides the soil parameter information on the specific soil series in question. Alternatively, a table of soil parameters for

127 selected locations is provided in Appendix B and can be used to provide the necessary information for the PLA calculation.

## Concrete USTs

Generally, concrete USTs do not suffer the same types of degradation as do the steel USTs. However, in severe environments (i.e., soils with a high concentration of sulfates, soils with extremely low or extremely high pH, or areas of high seismic activity), the onset of concrete structure deterioration (e.g., dissolution, degradation due to chemical reactions, mechanical damage, or disruption due to volume expansion) may be worsened (Troxell, Davis, and Kelly 1968).

Specifically, the factors to be considered in assessing the potential for deterioration of concrete USTs are as follows:

- soil pH < 4.5
- soil pH > 9.0
- soil $SO_4$ concentration > 0.20 percent
- freeze-thaw cycles
- time of exposure to the severe environment
- exposure to extreme seismic activity (accelerations > 5%g*)
  (* 1 g = acceleration magnitude of 9.81 m/sec$^2$)

One of these deterioration factors, freeze-thaw cycles, may occur in situations where part of the structure is above the frost line in severely cold climates. A map of frost line isobaths through the United States is available from the Water Survey Atlas of the United States (Geraghty et al. 1973). Another way to determine if freeze-thaw degradation is likely to occur in a given location is to examine nearby building foundations for structural defects. The foundations are located above the frost line, so they are more susceptible to freeze-thaw conditions than are structures below the frost line. Damaged building foundations are tell-tale signs that the concrete USTs may also be damaged. Generally, at least 1 ft of backfill covers the top of the tank, so no part of the concrete UST should ever be found at a depth of less than 1 ft below the surface.

Cracked foundations and other above-surface damage could also indicate the damaging effects of severe seismic activity. Reports of such activity over the life cyle of the concrete UST should be considered when assessing probable structural degradation. Generally, a concrete UST should be monitored for leakage,

after it has be subjected to a severe seismic event. Figure 3 shows a seismic activity map available from the U.S. Geological Survey website, which may be accessed through "http://gldage.cr.usgs.gov/eq/finmaps/shtml)." Archival data indicates that most of the UST leakage that occurs following seismic events is a result of loosened or ruptured pipe joints; therefore, *steel* USTs should also be monitored for leakage following seismic events having accelerations greater than 5%g (Perkins and Wyatt 1990).

Based on the above information, a concrete UST leak risk (CUSTLR) assessment procedure has been developed. It is based on an index for which 1 point is added as each threshold condition is exceeded. The computation of the CUSTLR Index proceeds as follows:

Start with CUSTLR = 0

| | |
|---|---|
| If UST is older than 15 years | add 1 |
| If surrounding soil pH < 4.5 *or* if pH > 9.0 | add 1 |
| If $SO_4$ concentration > 0.2percent (sulfide index =1) | add 1 |
| If freeze-thaw conditions exist | add 1 |
| If UST is subjected to extreme seismic activity with accelerations > 5% g (see seismic map in Figure 3) | add 1 |
| CUSTLR Index = TOTAL | ______ |

(Appendix B may be used to obtain the necessary soil information for the UST location.)

The CUSTLR Index is interpreted as follows:

| CUSTLR | Leak Risk for Concrete USTs |
|---|---|
| 0-1 | Low |
| 2-3 | Medium |
| 4-5 | High |

For example, for a concrete UST that has been in service for 20 years in a soil with a pH > 9.5, with $SO_4$ < 0.2, subject to freeze-thaw, but not subject to seismic activity, the CUSTLR Index rank is 3.

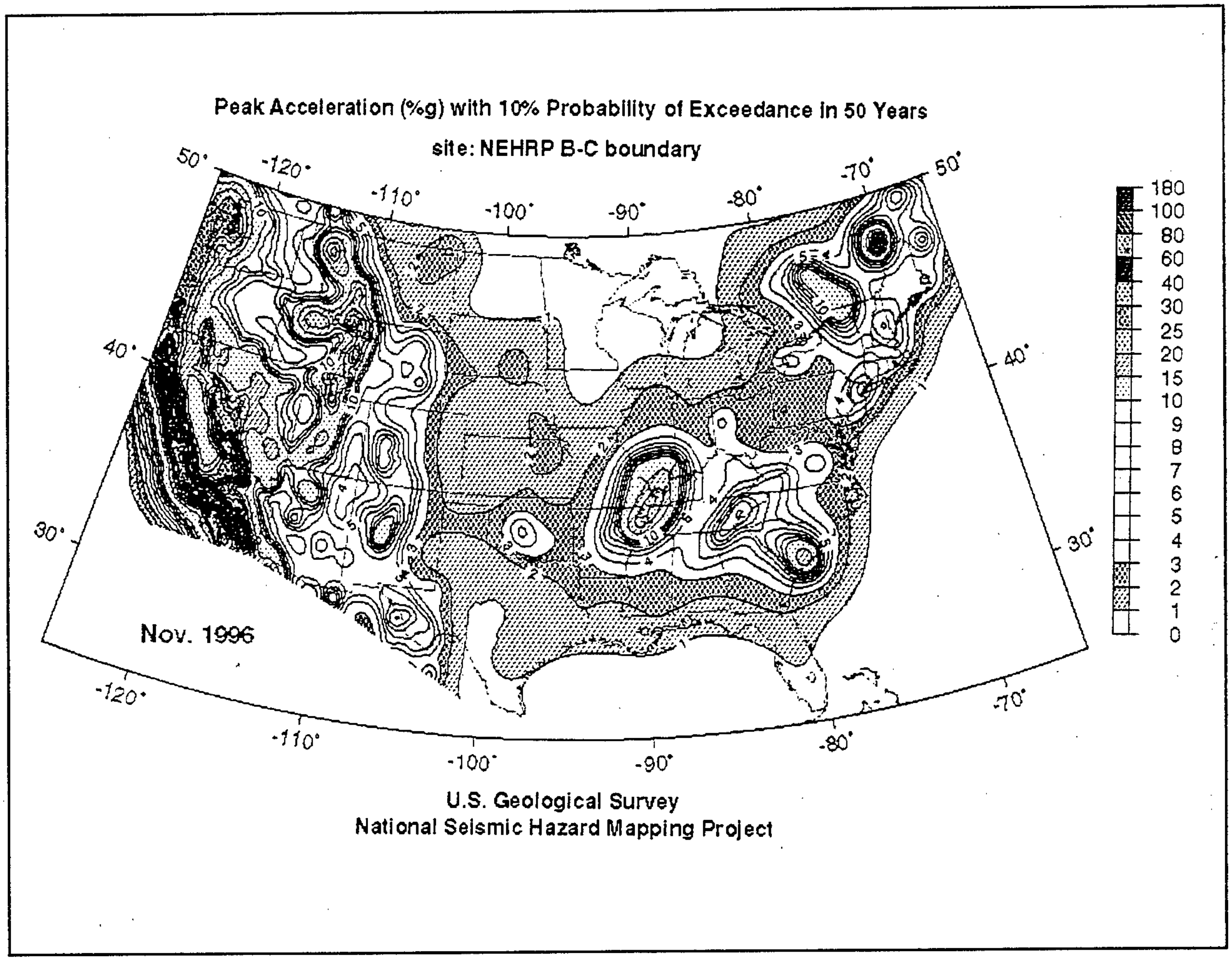


**Figure 3. Seismic activity map.**

# 8 Testing the New Model With FUDS Field Data: Results/Revisions

The new MLPI was evaluated against FUDS field data, provided as a set of minimal information on 49 USTs, 19 of which were known to be leaking. These leaking USTs were found in eight different sites, representing three U.S. states (see Appendix D). To yield a statistically significant test of the model, the data to be tested must provide a wide distribution of values over the range for which the model is to be used. Otherwise, the equations that comprise the regression matrix will be “ill-conditioned,” and the resulting model will not be robust.

Unfortunately, in the FUDS field data currently available, the leak/inspection ages for 75 percent of the test USTs are not well-defined (e.g., the information received indicated that the USTs were buried in the “early 1940s” or “early 1950s”; so about 50 percent of these USTs are the same approximate age (40 years). More than half of these USTs were of the same age, were buried in the same city or county, and apparently would be subjected to very similar soil properties. The only adequate variations in these data are the capacities (from which the thicknesses are also determined). A wider range of variance in the age and location data would be desired to be able to ascertain the model’s robustness. Of course, for the case at hand, the most important question is: “Does this particular set of field data accurately represent a reasonable cross-section of the actual FUDS USTs to be classified?”

The newly revised MLPI was evaluated on its ability to successfully predict low, medium, or high likelihood of UST leakage. Following the standard practice of hypothesis testing, a “null” hypothesis was formulated, and Type I and Type II Errors were assessed against the null hypothesis as follows:

- The *null hypothesis* is the UST is *NOT leaking*.
- Type I error = reject the null hypothesis when it is true (i.e., report the UST as “leaking” when it is NOT leaking).
- Type II error = accept the null hypothesis when it is false (i.e., report the UST as “NOT leaking” when it is leaking).

For this project, two new error categories have been developed:

- "0" meaning "no error", i.e, "correct prediction."
- "T" meaning "tossup," since the tank has a Level 2 chance of leaking and, therefore, is most likely not leaking at this time, but the prediction indicates that its leak age is imminent.

Table 7 explains these types of errors and their use in hypothesis testing.

The MLPI model was then re-evaluated, and had to be rescaled to accommodate the new data, with a bias toward not committing any Type II errors, so tanks that were leaking would not be reported as nonleaking. The model was further adjusted by using STDs from a set of 97 leaking USTs in the TANKMAN database with an average leak age and leak age standard deviation were determined as a function of the tank wall thickness, as shown in Table 8. When these adjustments were made, the MLPI was re-evaluated. The results are shown in Table 9.

**Table 7. Explanation of types of errors in hypothesis testing of FUDS MLPI with FUDS field data.**

| MLPI | Is UST Leaking? | Type Error |
|---|---|---|
| 1 | YES | II |
| 2 | YES | 0 |
| 3 | YES | 0 |
| 1 | NO | 0 |
| 2 | NO | T |
| 3 | NO | I |

**Table 8. Standard deviation in UST predicted leak age as a function of UST shell thickness and capacity.**

| Tank Capacity (gal)[a] | Shell Thickness (in.)[b] | Standard Deviation |
|---|---|---|
| ≤ 285 | 0.078 | 15 |
| 286 to 550 | 0.109 | 13.45 |
| 551 to 1,500 | 0.141 | 14.38 |
| 1,501 to 4,000 | 0.188 | 12.98 |
| 4,001 to 11,600 | 0.250 | 11.07 |
| 11,601 to 20,000 | 0.313 | 10.4 |
| 20,001 to 30,000 | 0.375 | 10 |
| 30,001 to 100,000 | 0.500 | 10 |
| ≥100,000 | 0.625 | 10 |

Table 9. MLPI model evaluation.

| "0" Errors (%) | Type I Errors (%) | Type II Errors (%) | Type "T" Errors (%) |
|---|---|---|---|
| 47 | 6 | 0 | 47 |

Thus, the FUDS leak prediction model finally chosen as a result of this study was the hybrid model generated with the data for 60 leaking USTs from the Warren Rogers database, and data from the 23 leaking USTs from the TANKMAN database, with the constant term adjusted upwards by a factor of 1.66 in order to fit the FUDS field data provided.

The final MLPI is now given as:

$$PLA = AR^{B}S^{C}T^{F}[\exp(\alpha pH + \beta M + \gamma Su)]$$

where:

$A = 425$,

$B = 0.072624$

$C = -0.194713$

$F = 0.862292$

$\alpha = 0.000392$

$\beta = -0.195012$

$\gamma = -0.067732$

with the STD given in Table 8.

The variables S, T, R, pH, M, Su are defined as:

PLA = Predicted Leak Age (years)

S = tank capacity (gallons)

T = tank's original wall (shell) thickness (inches)

R = soil resistivity R (ohm-cm)

pH = pH (dimensionless)

M = relative moisture content (dimensionless, 1, or 0)

Su = relative sulfide content (dimensionless, 1, or 0).

Also note that:

M = 1 if the soil >28%; otherwise, M = 0

Su = 1 if sulfide content > 0.5 ppm; otherwise, Su = 0.

Using the UST's PLA value and the relevant STD, the z-statistic may be calculated in accordance with Equation 10, and the MLPI may be determined from Table 6.

# 9 Conclusions and Recommendations

## Conclusions

Leak risk assessment indices for steel and concrete USTs have been developed. The modified leak potential index (MLPI) algorithms for steel and concrete USTs given in this report are relatively easy to use, and are expected to be easy to incorporate into electronic databases. The MLPI prediction models can be used as part of a triage program to prioritize the order in which tanks should be removed. The MLPI can be further modified as new UST leak and surrounding soil data are accumulated.

## Recommendations

It is suggested that the LPI model and protocol be incorporated into U.S. Army Corps of Engineers' standing procedures for selection and prioritization of UST removals at FUDS.

More information on the various soil series (and associated taxonomic classifications) in the United States is expected to be available in the near future, perhaps in a convenient personal computer (PC) accessible database. Based on this information and on the combination of data capabilities currently available (both in print and on PC), it is recommended that a single database ultimately be developed to automatically provide the actual, necessary soil parameters for the given location in question in order to computer the MLPI for a UST at that location.

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# Appendix A: Mathematical Abbreviations and Acronyms

## Mathematical Abbreviations

| | |
|---|---|
| A, B, C, D, F | Constants to be determined by regression analysis |
| Age | Age of UST at the time of inspection (years) |
| $\alpha, \beta, \gamma$ | chemistry parameters |
| E | chemistry term of the Leak Prediction Model |
| | $= \exp(\alpha pH + \beta M + \gamma Su)$ |
| f, g | unspecified (generic) mathematical functions |
| | g = acceleration due to gravity = 32 ft/sec$^2$ |
| | (when used in seismic events context in this report) |
| k | constant in the Romanoff Equation |
| PLA | Predicted Leak Age of UST when first leak occurs (in years) |
| M | 1 if soil moisture >28%; 0 otherwise |
| MGP | MicroGPIPER Equation |
| N | exponent in the Romanoff Equation |
| $P_s$ | Probability of Survival |
| Pr(z) | probability that leak has occurred |

| | |
|---|---|
| $p_{max}$ | maximum pit depth |
| pH | pH of the soil (dimensionless) |
| R | Resistivity (ohm-cm) |
| r | regression coefficient |
| Su | 1 if sulfide content >0.5 ppm, 0 otherwise |
| S | Tank Capacity (gallons) |
| STD | standard deviation |
| T | wall (or "shell") thickness (UST or pipe) (in.) |
| t | time of exposure to corrosive environment |
| WR | Warren Rogers Equation |
| z | statistical variable |

## Other Acronyms and Abbreviations

| | |
|---|---|
| ABAG | Association of Bay Area Governments |
| Ave | Arithmetic Mean |
| BTEX | Benzene, Toluene, Ethylbenzene, Xylene |
| CHF | Contaminant Hazard Factor |
| CON/HTRW | Containerized Hazardous Toxic Radioactive Waste |
| CUSTLR | Concrete UST Leak Risk |
| FUDS | Formerly Used Defense Sites |
| LPI | Leak Potential Index |

| | |
|---|---|
| MLPI | Modified Leak Potential Index |
| MPF | Migration Pathway Factor |
| PLA | Predicted Leak Age (of UST) |
| POL | Petroleum, Oil, Lubricants |
| RF | Receptor Factor |
| STD | Standard Deviation |
| UST | underground storage tank |
| WR | Warren Rogers (Leak Age Prediction Equation) |

# Appendix B: Soil Types and Relevant Parameters for Selected U.S. Locations

| Site # | State | City/County | Soil Type | Resistivity (Ohm-cm) | pH | Sulfate Concentration | Sulfate Index | Moisture Index |
|---|---|---|---|---|---|---|---|---|
| 1 | Alabama | Mobile | Kalmia fine sandy loam | 8,290 | 4.4 | 0 | 0 | 1 |
| 2 | Arizona | Phoenix | Mohave fine gravelly loam | 232 | 8 | 2.97 | 1 | 0 |
| 3 | Arizona | Phoenix | Gila clay | ? | ? | 0 | 0 | 0 |
| 4 | California | Oakland | Dublin Clay adobe | 1,345 | 7 | 0.25 | 1 | 1 |
| 5 | California | Los Angeles | Hanford fine sandy loam | 3,190 | 7.1 | 0.14 | 0 | 1 |
| 6 | California | Bakersfield | Hanford very fine sandy loam | 290 | 9.5 | 3.76 | 1 | 0 |
| 7 | California | Buttonwillow | Merced silt loam | 278 | A?? | 5.57 | 1 | 0 |
| 8 | California | San Diego | Montezuma clay adobe | 408 | 6.8 | 0.89 | 1 | 0 |
| 9 | California | Los Angeles | Romona loam | 2,060 | 7.3 | 0.35 | 1 | 0 |
| 10 | California | Tranquillity | Merced clay adobe | 128 | 7.7 | 37.5 | 1 | 0 |
| 11 | California | Cholame | Docas clay | 62 | 7.5 | 0.26 | 1 | 0 |
| 12 | California | Wilmington | Chino silt loam | 148 | 8 | 16.9 | 1 | 0 |
| 13 | California | Buttonwillow | Merced silt loam | 278 | 9.4 | 5.57 | 1 | 0 |
| 14 | California | Los Angeles | Chino silt loam | 2,650 | 9.2 | 0.15 | 0 | 0 |
| 15 | California | Fresno | Fresno fine sandy loam | 497 | 8.4 | 0.25 | 1 | 0 |
| 16 | California | Fresno | Fresno fine sandy loam | 531 | 10.2 | 23.11 | 1 | 0 |
| 17 | California | Kernell | Fresno fine sandy loam | 51 | 7.3 | 23.11 | 1 | 0 |
| 18 | California | Niland | Imperial clay (mod. alkali) | 149 | 7.4 | 25.98 | 1 | 0 |

| Site # | State | City/County | Soil Type | Resistivity (Ohm-cm) | pH | Sulfate Concentration | Sulfate Index | Moisture Index |
|---|---|---|---|---|---|---|---|---|
| 19 | California | Niland | Imperial clay (mod. alkali) | 102 | 7.4 | 4.06 | 1 | 0 |
| 20 | California | Los Banos | Merced clay | 320 | 9.2 | 1.57 | 1 | 0 |
| 21 | California | Tranquillity | Merced clay loam adobe | 106 | 8.5 | 46.53 | 1 | 0 |
| 22 | California | Niland | Niland gravelly sand (low alkali) | 273 | 7.3 | 0.86 | 1 | 0 |
| 23 | California | Long Beach | Hanford fine sandy loam | 553 | 8.9 | ? | 1 | 0 |
| 24 | California | Mendota | Merced clay loam | 61 | 8.9 | ? | 1 | 0 |
| 25 | California | Cholame | Docas clay | 155 | 8.4 | ? | 1 | 0 |
| 26 | California | Los Angeles | White alkali soil | 93 | 7.3 | ? | 1 | 0 |
| 27 | California | Los Angeles | Black alkali soil | 1,700 | 9.2 | ? | 1 | 0 |
| 28 | California | Mendota | Panoche clay loam | 552 | 7.4 | 4.4 | 1 | 0 |
| 29 | Colorado | Denver | Unidentified sandy loam | 1,500 | 7 | 0 | 0 | 0 |
| 30 | Colorado | Rocky Ford | Otero clay loam | 436 | 7.3 | 26.22 | 1 | 0 |
| 31 | Colorado | Grand Junction | Billings silt loam | 261 | 7.3 | 22.48 | 1 | 0 |
| 32 | Colorado | Grand Junction | Billings silt loam | 103 | 7.3 | 36.82 | 1 | 0 |
| 33 | Colorado | Grand Junction | Billings silt loam | 81 | 7.3 | 25.7 | 1 | 0 |
| 34 | Delaware | Wilmington | Sassafras silt loam | 7,440 | 5.6 | 0 | 0 | 1 |
| 35 | Florida | Jacksonville | Norfolk fine sand | 20,500 | 4.7 | 0 | 0 | 1 |
| 36 | Florida | Jacksonville | St. John's fine sand | 11,200 | 3.8 | 0 | 0 | 1 |
| 37 | Florida | Pensacola | Norfolk sand | 34,400 | 5.7 | 0 | 0 | 1 |
| 38 | Florida | Tampa | Norfolk sand | 16,400 | 4.8 | 0 | 0 | 1 |
| 39 | Florida | W. Palm Beach | Muck | 1,180 | 4.3 | ? | 1 | 1 |
| 40 | Florida | Miami | Muck | 1,650 | 5.7 | ? | 1 | 1 |
| 41 | Georgia | Atlanta | Cecil Clay Loam | 300,000 | 5.2 | 0 | 0 | 1 |
| 42 | Georgia | Atlanta | Cecil clay loam | 17,790 | 4.8 | 0 | 0 | 1 |
| 43 | Georgia | Macon | Cecil clay loam | 28,000 | 4.8 | 0 | 0 | 1 |
| 44 | Georgia | Atlanta | Cecil gravelly loam | 44,400 | 4.9 | 0.18 | 0 | 1 |
| 45 | Georgia | Atlanta | Cecil clay loam | 43,800 | 5.8 | ? | 1 | 1 |

| Site # | State | City/County | Soil Type | Resistivity (Ohm-cm) | pH | Sulfate Concentration | Sulfate Index | Moisture Index |
|---|---|---|---|---|---|---|---|---|
| 46 | Illinois | East St. Louis | Wabash silty clay loam | 521 | 6.8 | 1.99 | 1 | 1 |
| 47 | Illinois | Mt. Auburn | Muscatine silt loam | ? | 6.1 | ? | 1 | 1 |
| 48 | Indiana | Preble | Miami silt loam | 2,200 | 6.3 | ? | 1 | 1 |
| 49 | Iowa | Des Moines | Lindley silt loam | 1,970 | 4.6 | 0.15 | 0 | 1 |
| 50 | Iowa | Davenport | Muscatine silt loam | 1,300 | 7 | 0.21 | 0 | 1 |
| 51 | Kansas | Arkansas City | Oswego silt loam | 1,295 | 7 | ? | 1 | 0 |
| 52 | Kansas | Caney | Oswego silt loam | 3,510 | 5.4 | ? | 1 | 0 |
| 53 | Louisiana | Bunkie | Miller clay | 570 | 6.6 | 1.51 | 1 | 1 |
| 54 | Louisiana | New Orleans | Muck | 1,270 | 4.2 | 2.3 | 1 | 1 |
| 55 | Louisiana | New Orleans | Sharkey clay | 970 | 6 | 0.28 | 1 | 1 |
| 56 | Louisiana | New Orleans | Muck | 712 | 4.8 | 2.54 | 1 | 1 |
| 57 | Louisiana | New Orleans | Sharkey clay | 943 | 6.8 | 0.91 | 1 | 1 |
| 58 | Louisiana | Shreveport | Susquehanna clay | 6,840 | 4.1 | 0 | 0 | 1 |
| 59 | Louisiana | Shreveport | Susquehanna sandy clay loam | 577 | 3.9 | 0 | 0 | 1 |
| 60 | Louisiana | Bunkie | Miller clay | 674 | 7.9 | ? | 1 | 1 |
| 61 | Louisiana | Shreveport | Susquehanna clay | 6,840 | 4.6 | ? | 1 | 1 |
| 62 | Louisiana | Shreveport | Miller clay | 870 | 7.4 | ? | 1 | 1 |
| 63 | Maryland | Loch Raven | Hagerstown Loam | 11,000 | 5.3 | 0 | 0 | 1 |
| 64 | Maryland | Loch Raven | Hagerstown loam | 5,210 | 5.8 | 0 | 0 | 1 |
| 65 | Massachusetts | Middleboro | Gloucester Sandy Loam | 7,460 | 6.6 | 0 | 0 | 1 |
| 66 | Massachusetts | Norwood | Merrimac gravelly sandy loam | 11,400 | 12.6 | 0 | 0 | 1 |
| 67 | Massachusetts | Brockton | Tidal marsh | 44 | 3.6 | ? | 1 | 1 |
| 68 | Michigan | Kalamazoo | Carlisle muck | 1,660 | 5.6 | 1.04 | 1 | 1 |
| 69 | Minnesota | St. Paul | Hempstead silt loam | 3,520 | 6.2 | 0 | 0 | 1 |
| 70 | Mississippi | Meridian | Ruston sandy loam | 11,200 | 4.5 | 0 | 0 | 1 |

| Site # | State | City/County | Soil Type | Resistivity (Ohm-cm) | pH | Sulfate Concentration | Sulfate Index | Moisture Index |
|---|---|---|---|---|---|---|---|---|
| 71 | Mississippi | Meridian | Susquehanna clay | 13,700 | 4.7 | 0 | 0 | 1 |
| 72 | Mississippi | Meridian | Susquehanna clay | 6,920 | 4.5 | 0 | 0 | 1 |
| 73 | Mississippi | Louisville | Susquehanna clay | 9,390 | 4.3 | 0.05 | 0 | 1 |
| 74 | Mississippi | Vicksburg | Memphis silt loam | 3,450 | 6.9 | 0 | 0 | 1 |
| 75 | Missouri | Kansas City | Marshall silt loam | 2,370 | 9.5 | 0 | 0 | 1 |
| 76 | Missouri | Kansas City | Summit silt loam | 1,320 | 5.5 | 0.16 | 0 | 1 |
| 77 | Missouri | Kansas City | Marshall silt loam | 3,150 | 6.5 | ? | 1 | 1 |
| 78 | Nebraska | Omaha | Knox silt loam | 1,410 | 7.3 | 0.46 | 1 | 1 |
| 79 | Nebraska | Omaha | Wabash silt loam | 1,000 | 5.8 | 0.41 | 1 | 0 |
| 80 | New Jersey | Camden | Sassafras gravelly sandy loam | 38,600 | 4.5 | 0 | 0 | 1 |
| 81 | New Jersey | Elizabeth | Tidal marsh | 60 | 3.1 | 37 | 1 | 1 |
| 82 | New Jersey | Atlantic City | Tidal marsh | 32 | 3 | ? | 1 | 1 |
| 83 | New Mexico | Albuquerque | Unidentified silt loam | 379 | 8.4 | 5.58 | 1 | 0 |
| 84 | New York | Rochester | Ontario loam | 5,700 | 7.3 | 0.42 | 1 | 1 |
| 85 | North Carolina | Charlotte | Cecil clay | 8,500 | 4.6 | 0 | 0 | 1 |
| 86 | North Carolina | Salisbury | Cecil clay loam | 25,000 | 4.8 | 0 | 0 | 1 |
| 87 | North Carolina | Raleigh | Cecil fine sandy loam | 54,400 | 4.8 | 0 | 0 | 1 |
| 88 | North Carolina | Raleigh | Cecil clay loam | 16,000 | 6.9 | ? | 1 | 1 |
| 89 | North Dakota | Fargo | Fargo Clay Loam | 350 | 7.6 | 0 | 0 | 0 |
| 90 | Ohio | Cincinnati | Maddox Silt Loam | 2,120 | 4.4 | 4.43 | 1 | 1 |
| 91 | Ohio | Sidney | Genesee Silt Loam | 2,820 | 6.8 | 0 | 0 | 1 |
| 92 | Ohio | Cleveland | Mahoning silt loam | 2,870 | 7.5 | 0 | 0 | 1 |

| Site # | State | City/County | Soil Type | Resistivity (Ohm-cm) | pH | Sulfate Concentration | Sulfate Index | Moisture Index |
|---|---|---|---|---|---|---|---|---|
| 93 | Ohio | Springfield | Miami silt loam | 2,980 | 7.3 | 0.12 | 0 | 1 |
| 94 | Ohio | Cincinnati | Fairmount silt | 886 | 7 | 9.05 | 1 | 1 |
| 95 | Ohio | Plymouth | Rifle peat | 218 | 2.6 | 56.7 | 1 | 1 |
| 96 | Ohio | West Austintown | Mahoning silt loam | 2,582 | 7.1 | 0.27 | 1 | 1 |
| 97 | Ohio | Deerfield | Papakating silty clay loam | 762 | 7.2 | 11.58 | 1 | 1 |
| 98 | Ohio | Cleveland | Allis Silt Loam | 1,215 | 7 | 0.83 | 1 | 1 |
| 99 | Oklahoma | Council Hill | Unidentified | 5,180 | 5.5 | ? | 1 | 0 |
| 100 | Oklahoma | Skiatook | Unidentified | 440 | 5.2 | ? | 1 | 0 |
| 101 | Pennsyl-vania | Jenkintown | Chester Loam | 6,670 | 5.6 | 0 | 0 | 1 |
| 102 | Pennsyl-vania | Norristown | Pennsylvania silt loam | 4,900 | 6.7 | 0 | 0 | 1 |
| 103 | Pennsyl-vania | Chambersburg | Hagerstown loam | 5,090 | 6.4 | ? | 1 | 1 |
| 104 | Pennsyl-vania | Pittsburgh | Cinders | 730 | 5.5 | ? | 1 | 1 |
| 105 | South Carolina | Charlestown | Tidal marsh | 84 | 6.9 | 36.6 | 1 | 1 |
| 106 | Tennessee | Memphis | Memphis silt loam | 5,150 | 9.7 | 0 | 0 | 1 |
| 107 | Texas | Dallas | Bell Clay | 684 | 7.3 | 0.18 | 0 | 0 |
| 108 | Texas | San Antonio | Houston black clay | 489 | 7.5 | 0.73 | 1 | 0 |
| 109 | Texas | Spindletop | Acadia clay | 490 | 6.2 | 22 | 1 | 1 |
| 110 | Texas | League City | Lake Charles clay loam | 234 | 8.8 | 1.26 | 1 | 1 |
| 111 | Texas | El Vista | Lake Charles clay | 406 | 7.1 | 3.04 | 1 | 0 |
| 112 | Texas | Latex | Caddo fine sandy loam | 821 | 4.5 | 0.74 | 1 | 0 |
| 113 | Texas | El Vista | Lake Charles clay | 320 | 7.4 | 0.63 | 1 | 1 |
| 114 | Texas | Troup | Susquehanna clay | 4,460 | 4.1 | 0 | 0 | 1 |
| 115 | Texas | Temple | Bell clay | 947 | 8.4 | ? | 1 | 0 |

| Site # | State | City/County | Soil Type | Resistivity (Ohm-cm) | pH | Sulfate Concentration | Sulfate Index | Moisture Index |
|---|---|---|---|---|---|---|---|---|
| 116 | Texas | Beaumont | Lake Charles clay | 495 | 7.1 | ? | 1 | 0 |
| 117 | Texas | League City | Lake Charles clay | 1,485 | 7.2 | ? | 1 | 0 |
| 118 | Texas | Spindletop Gully | Acadia clay | 259 | 5.4 | ? | 1 | 0 |
| 119 | Texas | Bryan | Miller clay | 1,000 | 7.2 | ? | 1 | 0 |
| 120 | Utah | Salt Lake City | Unidentified silt loam | 1,770 | 7.6 | 0.18 | 0 | 0 |
| 121 | Virginia | Alexandria | Keyport loam | 5,980 | 4.5 | 0.25 | 1 | 1 |
| 122 | Washington | Seattle | Everett gravelly sandy loam | 45,100 | 5.9 | 0 | 0 | 1 |
| 123 | Wisconsin | Milwaukee | Miami Clay loam | 1,780 | 4.7 | 0.1 | 0 | 1 |
| 124 | Wisconsin | Milwaukee | Peat | 800 | 6.8 | 2.13 | 1 | 1 |
| 125 | Wisconsin | Milwaukee | Cinders | 455 | 7.6 | 2.89 | 1 | 1 |
| 126 | Wisconsin | Milwaukee | Cinders | 380 | 8 | ? | 1 | 1 |
| 127 | Wyoming | Casper | Unidentified alkali soil | 263 | 7.4 | 11.98 | 1 | 0 |

# Appendix C: Flow Charts for MLPI Calculations

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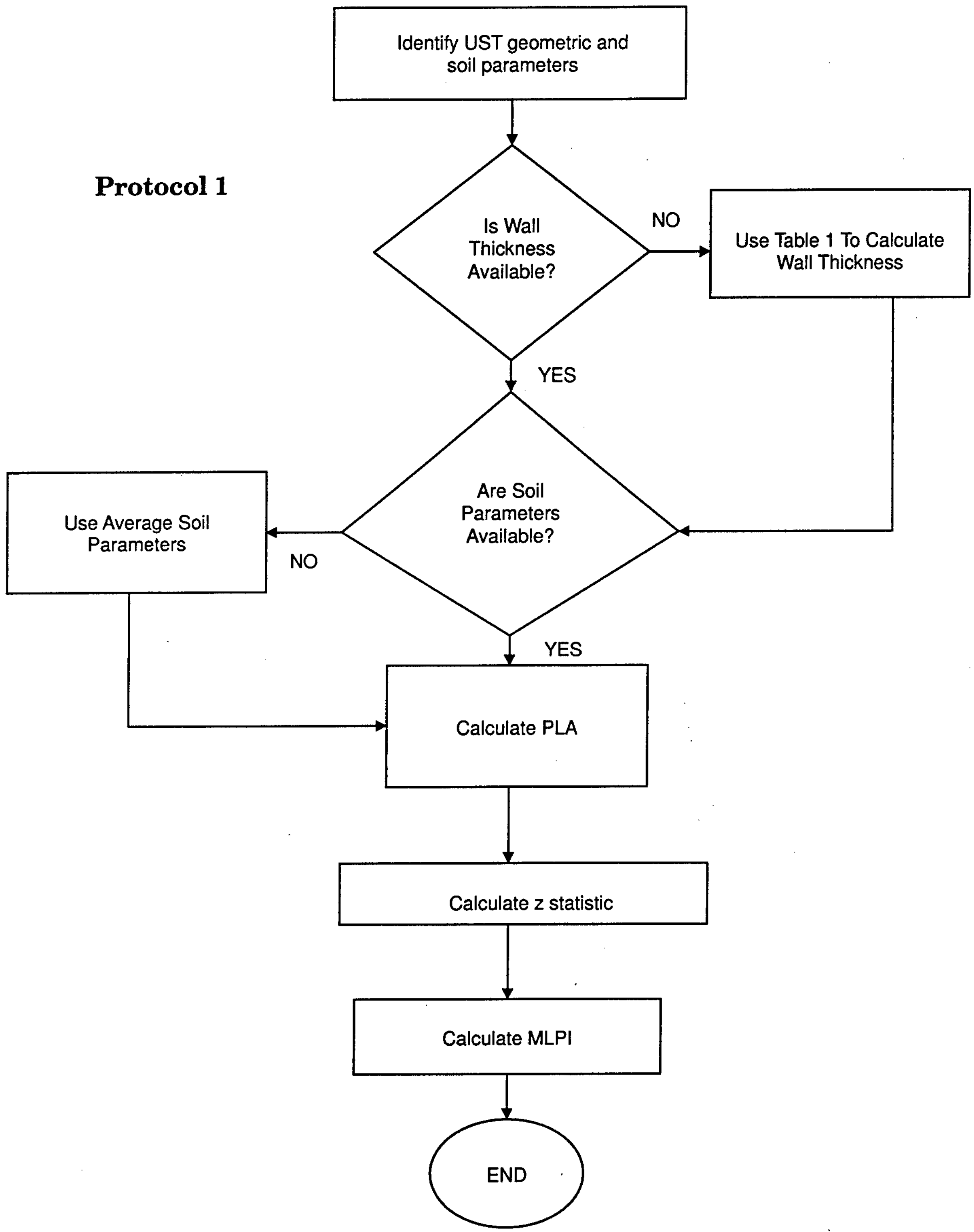
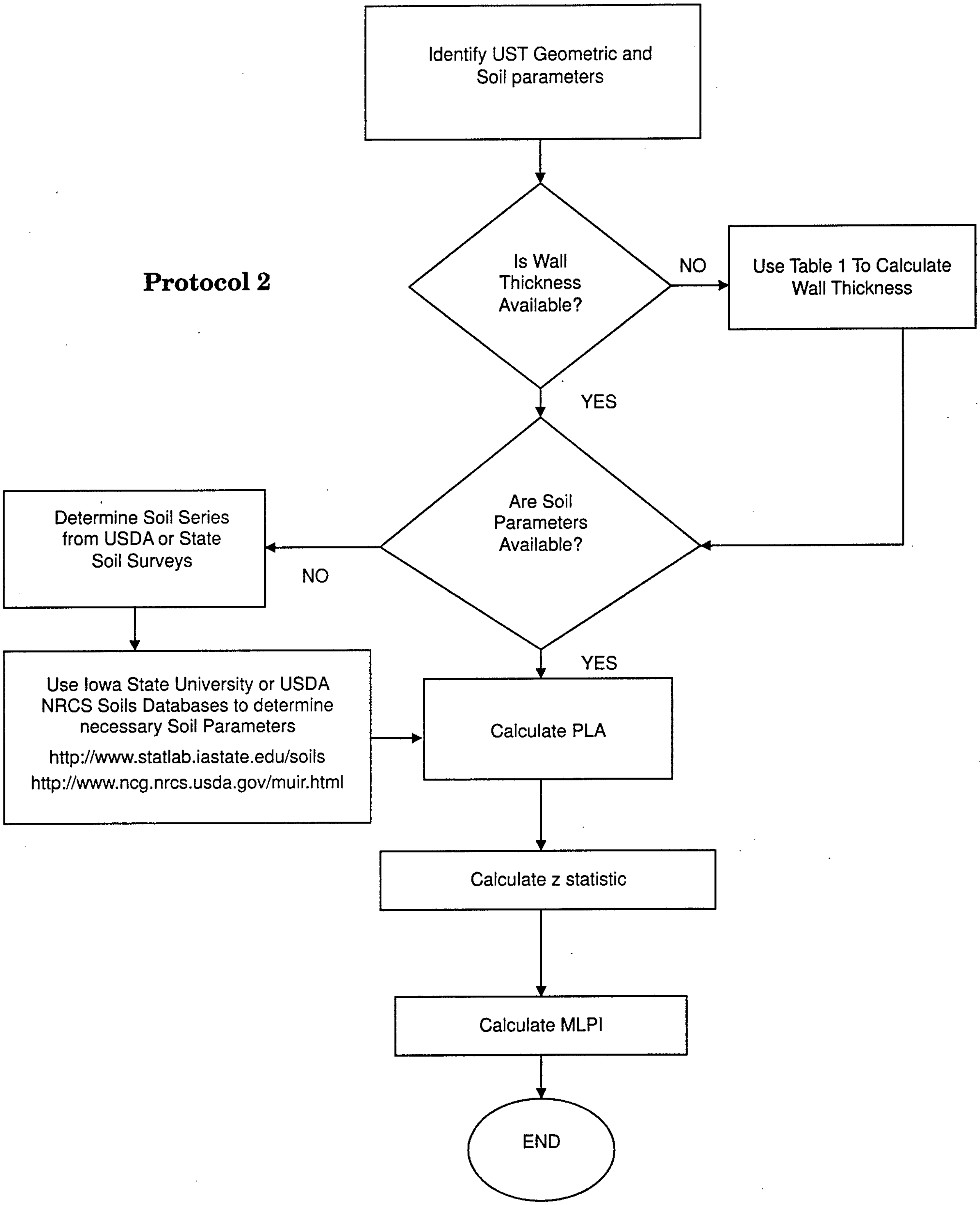
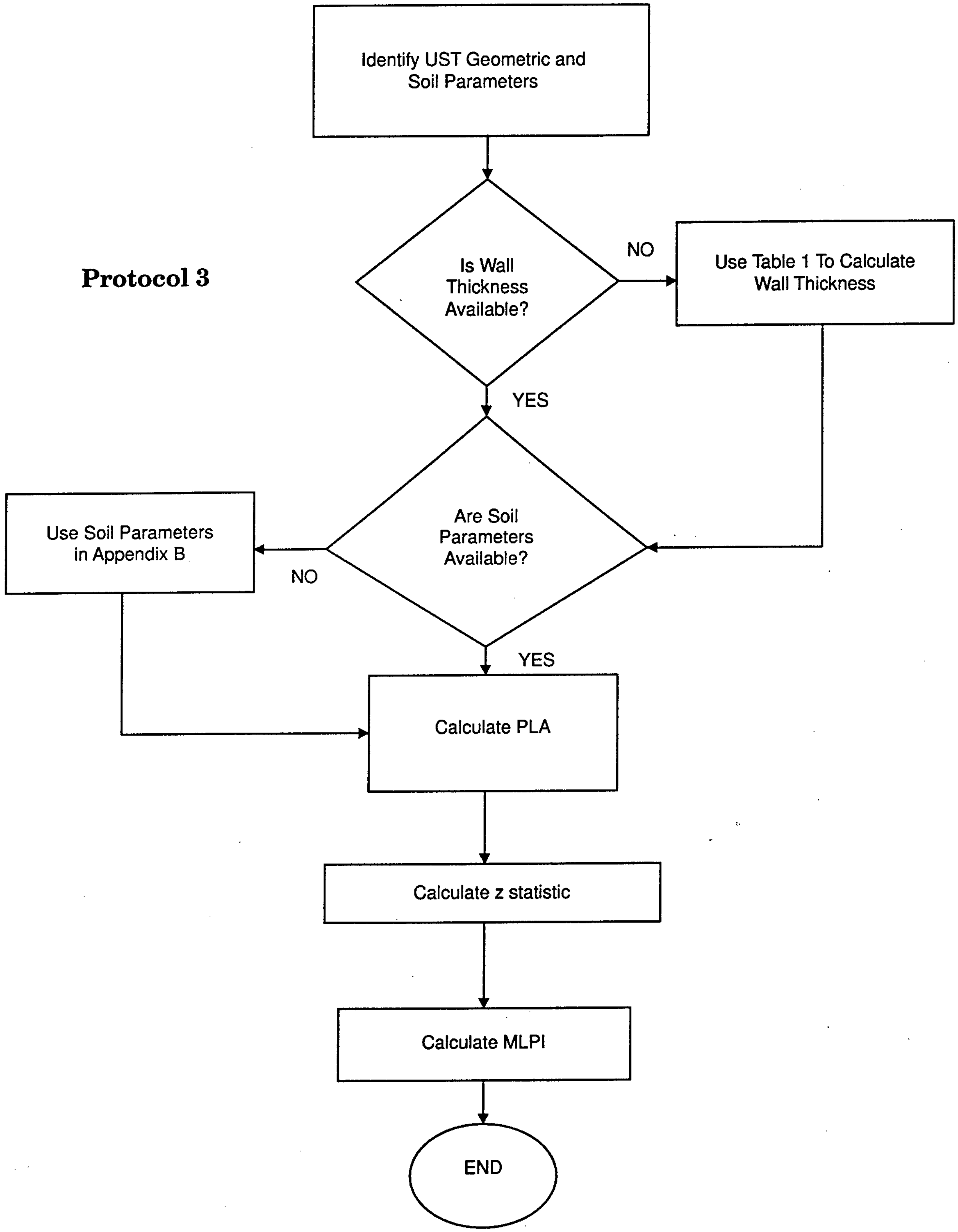
**Protocol 1**


Identify UST geometric and soil parameters
Is Wall Thickness Available?
NO
Use Table 1 To Calculate Wall Thickness
YES
Are Soil Parameters Available?
NO
Use Average Soil Parameters
YES
Calculate PLA
Calculate z statistic
Calculate MLPI
END

**Protocol 2**


Identify UST Geometric and Soil parameters
Is Wall Thickness Available?
NO
Use Table 1 To Calculate Wall Thickness
YES
Are Soil Parameters Available?
NO
Determine Soil Series from USDA or State Soil Surveys
Use Iowa State University or USDA NRCS Soils Databases to determine necessary Soil Parameters
http://www.statlab.iastate.edu/soils
http://www.ncg.nrcs.usda.gov/muir.html
YES
Calculate PLA
Calculate z statistic
Calculate MLPI
END

**Protocol 3**


Identify UST Geometric and Soil Parameters
Is Wall Thickness Available?
NO
Use Table 1 To Calculate Wall Thickness
YES
Are Soil Parameters Available?
Use Soil Parameters in Appendix B
NO
YES
Calculate PLA
Calculate z statistic
Calculate MLPI
END

# Appendix D: Data Used for FUDS Test

## Information on FUDS USTs in the Little Rock District

Southwestern Proving Ground, K06AR005102, one 5,000-gal tank, wall thickness unknown, Hope, Hempstead Co., Arkansas, tank age estimated to be over 50 years, not leaking.

Army/Navy Hospital Hot Springs, K06AR012001, one 15,000-gal and three 5,000-gal tanks, wall thickness unknown, Hot Springs, Garland Co., Arkansas, tank age estimated to be over 50 years, not leaking.

Little Rock Communications Transmitter, K06AR061401, two 2,000-gal tanks, wall thickness unknown, Jacksonville, Pulaski Co., Arkansas, tank age estimated to be over 50 years, not leaking.

## Data From the Fort Worth and Albuquerque Districts

### *Fort Worth District*

**Fort Wolters AAF, K06tx003408**
Mineral Wells, Palo Pinto County, TX

Three 12,000-gal tanks - did not leak
Age: early 1950s
Wall thickness – unknown.

23 5,000-gal tanks - 13 leaked
Age: early 1950s
Wall thickness – unknown.

**James Connaly AFB, K06TX0022000**
Waco, McLennan County, TX

Two 25,000-gal tanks did not leak
Age: early 1940s
Wall thickness – unknown.

Four 12,000-gal tanks, 2 leaked
Age: early 1940s
Wall thickness – unknown.

One 10,000-gal tank, did not leak
Age: early 1940s
Wall thickness – unknown.

Three 1,000-gal tanks, 2 leaked
Age: early 1940s
Wall thickness- unknown.

One 500-gal tank, leaked
Age: early 1940s
Wall thickness – unknown.

One 300-gal tank, did not leak
Age: early 1940s
Wall thickness –unknown.

**Comstock Gap Filler Annex, K06TX027401**
Comstock, Val Verde County, TX

One 3,000-gal tank, did not leak
Age: 1957
Wall thickness: unknown.

## *Albuquerque District*

**Tank Removals at former Walker AFB, NM**
**INPR # K00NM005200**

Tank #1
Size: 25,000 gal
Wall thickness: 5/16 in.
Location: Roswell, Chaves, NM
Age of tank: Installed 1962, last used: 1985
Leaked? No

Tank #2
Size: 8,000 gal
Wall thickness: 5/16 in.
Location: Roswell, Chaves, NM
Age of tank: Installed 1962, last used: 1969
Leaked? No

Tank #3
Size: 300 gal
Wall thickness: 0.135 in.
Location: Roswell, Chaves, NM
Age of tank: Installed 1950, last used: 1969
Leaked? Yes

## Distribution

Chief of Engineers
ATTN: CEMP-RF (2)

Corps of Engineers
ATTN: CESWT-EC-DR
ATTN: CESWT-PP-MEF
ATTN: CENAN-PL-EA
ATTN: CESWD-PMM
ATTN: CENED-PD-M
ATTN: CENCR-ED-O

U.S. Army Engr District
ATTN: Library (42)
ATTN: CELRH-DL-M (2)
ATTN: CELRL-DL-B (2)
ATTN: CELRN-ER-M (2)
ATTN: CEPOA-PM-E-F (2)
ATTN: CESAJ-S (2)
ATTN: CESAC-PM-S
ATTN: CESAM-PM-SP (2)
ATTN: CESAS-PM-H (2)
ATTN: CESAW-PM-C
ATTN: CESAW-EP-PE
ATTN: CESPK-PM-M
ATTN: CESPL-PM
ATTN: CESPA-PP-M
ATTN: CESWT-PP-ME (2)
ATTN: CESWF-PM-J
ATTN: CESWL-PM-M

U.S. Army Engr Division
ATTN: Library (8)
ATTN: CELRD-OR-DL-M (2)
ATTN: CEPOD-ET-ES (2)
ATTN: CESAD-PM-M
ATTN: CESPD-PM-R (2)
ATTN: CESWD-PMM

90
3/97